PEAK-TO-AVERAGE POWER REDUCTION IN AN ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING SYSTEM

Technical Field

This invention relates to transmission systems and, more particularly, to Orthogonal Frequency Division Multiplexing (OFDM) transmission systems.

Background of the Invention

Orthogonal Frequency Division Multiplexing is used extensively in many transmission applications, for example, wireless communications systems, wireless LANs, Digital Audio Broadcasting, Digital Subscriber Loops, or the like. Unfortunately, a major disadvantage of an OFDM system is its large peak-to-average power ratio (PAPR). This results because OFDM is a multicarrier transmission system and, therefore, it is possible for the carrier components to align their phases and add coherently giving rise to large peak amplitudes. Several attempts have been made at solving this problem. In one attempt level-clipping is employed in which amplitudes above a prescribed threshold level are clipped before transmission. This affects the orthogonality of the OFDM symbols and, therefore increases the bit-error-rate. Other arrangements employ coding schemes to decrease the PAPR; however, the required coding overhead reduces the net transmission bit rate. In still other arrangements random phases are applied to the OFDM sub-carriers so that PAPR is reduced. However, the random phase information has to be supplied to the receiver in order to decode the received signal.

Summary of the Invention

These and other problems and limitations are overcome in accordance with the invention by advantageously employing a transmission arrangement in which random phases are used across the OFDM sub-carrier components and by employing differential encoding so that the phase information (i.e., phase values) does not have to be explicitly transmitted to a receiver.

More specifically, the OFDM data symbols are differentially encoded so that the phase information on the symbols that are multiplied together in the differential encoder is the same.

In a specific embodiment, assuming use of differential phase shift keying (DPSK) encoding, a phase sequence is employed having "V" random phase values, where $\theta_{n,k}$ is the phase value in the n^{th} sub-carrier in the k^{th} OFDM symbol and is periodic in n with V as the period. A current input symbol is then differentially encoded relative to the V^{th} previous encoded output from the encoder so that the phase values on the symbols multiplied together in the differential encoding process are the same. Advantageously, the differentially decoded output symbol at a remote receiver is substantially equal to the corresponding input symbol at the transmitter.

In another embodiment of the invention, V random phase values are employed in the phase sequences utilized in the differential encoding process and a threshold is set for a representation of the PAPR value at the transmitter. If the representation of the PAPR value is less than the threshold value, the corresponding OFDM symbol is transmitted. However, if the representation of the PAPR value exceeds the threshold value, the PAPR representation is re-computed using different random phase values until the PAPR representation value is below the threshold or until a prescribed number of iterations of the re-computation has been reached. Again, once the PAPR representation value is less than the threshold value, the corresponding OFDM symbol is transmitted. If the prescribed number of iterations has been reached, the computation process is terminated and the OFDM symbol that provided the smallest PAPR representation value is transmitted.

A significant technical advantage of the invention is that the phase sequence values employed at the transmitter do not have to be transmitted to the receiver along with the encoded symbols.

Brief Description of the Drawing

FIG. 1 shows, in simplified block diagram form, details of one embodiment of the invention;

FIG. 2 graphically illustrates a phase sequence useful in describing the invention;

FIG. 3 shows, in simplified block diagram form, details of another embodiment of the invention; and

FIG. 4 is a flow chart illustrating steps in a process for recomputing a PAPR representation value and useful in describing the embodiment of the invention shown in FIG. 3.

Detailed Description

FIG. 1 shows, in simplified block diagram form, details of one embodiment of the invention. In this embodiment of the invention, a differential phase shift keying (DPSK) system is used and a phase sequence $\{\theta_{n,k}\}$ having V random phase values α_v, where v = 0, 1, ..., (V – 1) is employed such that

$$\theta_{n'V+v,k} = \alpha_v , \qquad v = 0, 1, \ldots, (V-1) \quad , \tag{1}$$

where n' is an integer such that $0 \le (n'V + v) \le (N-1)$. That is, $\theta_{n,k}$ is periodic in n, with V as the period. An example phase sequence is shown in FIG. 2, where V = 3.

In this example, as shown in FIG. 1 differential phase shift keying (DSPK) encoder 101 generates

$$D^V_{n,k} = C_{n,k} D^V_{n-V,k} , \tag{2}$$

where $C_{n,k}$ is the complex data symbol input and $D^V_{n,k}$ is the differentially encoded output complex data symbol component in the n^{th} sub-carrier in the k^{th} OFDM symbol, corresponding to $C_{n,k}$. This is realized by supplying $C_{n,k}$ as an input to differential encoder 101 and, therein, to a first input of multiplier 102. An output $D^V_{n,k}$ is supplied to delay unit 103, which yields $D^V_{n-V,k}$. In turn, $D^V_{n-V,k}$ is supplied to a second input of multiplier 102 where it is multiplied with $C_{n,k}$ to yield $D^V_{n,k}$. Thus, the current input symbol $C_{n,k}$ is differentially encoded with respect to the V^{th} previous differentially encoded output $D^V_{n,k}$, namely, $D^V_{n-V,k}$. It is noted that differential encoder 101 is of a type known in the art. Then, $D^V_{n,k}$ is supplied to phase sequence unit 104 where it is multiplied by $e^{j\theta_{n,k}}$ to yield the inverse fast Fourier transform (IFFT), namely,

$$E_{n,k} = e^{j\theta_{n,k}} D^V_{n,k} , \qquad n = 0, 1, \ldots, (N\text{-}1). \tag{3}$$

Then, $E_{n,k}$ is supplied to inverse discrete Fourier transform (IDFT) unit 105 that generates the sequence of IDFT versions of $E_{n,k}$ denoted by $\{e_{m,k}\}$, for $m = 0,1,\ldots,(N-1)$ as follows:

$$e_{m,k} = \sum E_{n,k} e^{j\frac{2\pi}{N}nm}, \qquad m = 0, 1, \ldots, (N\text{-}1). \tag{4}$$

Sequence $\{e_{m,k}\}$ is digital-to-analog converted via D/A converter 106 to yield an analog signal representation of the transmitted baseband signal for the k^{th} OFDM symbol,

$$s_k^V(t) = \begin{cases} \dfrac{1}{\sqrt{T_s}} \sum_{n=0}^{N-1} e^{j\theta_{n,k}} D^V{}_{n,k} e^{j2\pi\frac{n}{T_s}t} & t \in [kT_0, (k+1)T_0] \\ 0 & otherwise \end{cases} \tag{5}$$

that is supplied to transmission channel 108 to be transported to a remote receiver, in known fashion. Thus, it is seen that equation (4) is used in equation (5) to determine the N transmit samples, $s_k^V(kT_0 + \frac{mT_s}{N}), m = 0,1,\ldots,(N-1)$, where T_0, the effective transmit duration of an OFDM symbol, is given by the sum of OFDM symbol interval T_s and the cyclic extension duration T_g. Also, the number of sub-carriers is N and the total bandwidth of the transmitted signal is approximately $\frac{N}{T_s}$.

At the remote receiver, a received version of $s_k^V(t)$, namely, $\hat{s}_k^V(t)$, is analog-to-digital converted via A/D converter 109 and the resultant digital signal is supplied to discrete Fourier transform unit 110 where a DFT is performed on the N samples to obtain

$$R_{n,k} = e^{j\theta_{n,k}} D_{n,k}^V, \qquad n = 0, 1, 2, \ldots, (N\text{-}1). \tag{6}$$

Note that in the above transform process channel impairments have been ignored such as fading and additive noise. Then, $R_{n,k}$ is differentially decoded, in this example, via differential phase shift keyed (DPSK) decoder 111 to yield

$$\hat{C}_{n,k} = R_{n,k} R_{n-V,k}^*, \tag{7}$$

where "*" indicates the complex conjugate. Using the relationships of equations (2) and (6) with equation (7), it can be shown that

$$\hat{C}_{n,k} = e^{j(\theta_{n,k}-\theta_{n-V,k})} C_{n,k}. \tag{8}$$

Since, $\theta_{n,k}$ has been chosen such that it is periodic in n, with period V, it can be shown that in the absence of channel impairments and noise that at the receiver

$$\hat{C}_{n,k} = C_{n,k}. \tag{9}$$

Thus, it is seen that there is no need to explicitly transmit the phase information, i.e., phase values, as overhead with the transmitted symbols, and the PAPR is reduced, in accordance with the invention.

FIG. 3 shows, in simplified block diagram form, details of another embodiment of the invention. The elements of the embodiment shown in FIG. 3 that are essentially identical as those employed in the embodiment of FIG. 1 have been similarly numbered and will not be described again in detail. As indicated above, it is not necessary to explicitly transmit the phase sequences $\{\theta_{n,k}\}$ because they are periodic in n and there are V random phases α_v, $v = 0, 1, \ldots, (V-1)$. It may be desirable to select a threshold value for the PAPR. Then, if the PAPR is equal to or less than the threshold the corresponding symbol is transmitted. However, if the PAPR exceeds the threshold value then the PAPR is recomputed using a different set of phase values α_v until it becomes equal to or less than the threshold. Since the computational power of the transmitter is limited, only a prescribed number of iterations of the recomputing process is made. Specifically, after the p^{th} iteration of the computation of PAPR, the OFDM symbol that yields the smallest value for PAPR is selected and transmitted.

To this end, the transmitter includes output control 301 for controlling, via $\{\theta_{n,k}\}$ selection processor 302, transmission of the OFDM symbols to a remote receiver. $\{\theta_{n,k}\}$ selection processor 302 also controls the selection of new phase values via select $\{\theta_{n,k}\}$ unit 303. Select $\{\theta_{n,k}\}$ unit 303 supplies the new phase values $\{\theta_{n,k}\}$ to phase sequence unit 104 where they are employed to generate new values for $E_{n,k}$.

FIG. 4 is a flow chart illustrating steps in a process for recomputing a PAPR representation value and useful in describing the embodiment of the invention shown in FIG. 3. Specifically, FIG. 4 is a flow chart of the operation of $\{\theta_{n,k}\}$ selection processor

302. Thus, the process is started in step 401. Thereafter, step 402 sets the iteration index $p = 0$, i.e., initializes the process. Step 403 generates a prescribed relationship $\sum_{m=0}^{N-1} |e_{m,k}|^2$, which is a representation of PAPR. To this end, sequence $\{e_{m,k}\}$, where $m = 0, 1, \ldots, (N-1)$, is supplied from inverse discrete Fourier transform unit 105. Then, step 404 tests to determine whether $\sum_{m=0}^{N-1} |e_{m,k}|^2 < Threshold$. If the test result in step 404 is YES, control is returned to step 402 and step 405 causes the current phase sequence $\{\theta_{n,k}\}$ to be selected by sending an appropriate control signal to select $\{\theta_{n,k}\}$ unit 303 (FIG. 3). Additionally, a control signal is supplied to transmission control 301 (FIG. 3) to enable it to transmit the corresponding OFDM symbol, i.e., to be in a transmit state. Note that transmission control 301 is normally in an inhibit transmission state. Returning to step 404, if the test result is NO, step 406 tests to determine if count < p, i.e., whether fewer than p recomputation iterations have been made. If the test result is YES, the p^{th} iteration has not been reached and step 407 causes a new phase sequence $\{\theta_{n,k}\}$ to be selected. To this end, an appropriate control signal is sent to select $\{\theta_{n,k}\}$ unit 303 (FIG. 3) in order to effect the selection. Additionally, step 408 sets $p = p+1$, and then control is returned to step 403 which recomputes $\sum_{m=0}^{N-1} |e_{m,k}|^2$ using the new sequence $\{e_{m,k}\}$ based on the new phase sequence $\{\theta_{n,k}\}$. Returning to step 406, if the test result is YES, the p^{th} recomputation iteration has been reached and the value of $\sum_{m=0}^{N-1} |e_{m,k}|^2$ is still greater than the Threshold value. In this instance step 409 then selects the phase sequence $\{\theta_{n,k}\}$ that yielded the smallest value for $\sum_{m=0}^{N-1} |e_{m,k}|^2$ during the p iterations. An appropriate control signal is sent to select $\{\theta_{n,k}\}$ unit 303 (FIG. 3) in order to effect the selection. Also, a control signal is supplied to transmission control 301 (FIG. 3) to enable it to transmit the corresponding OFDM symbol. Control is also returned to step 402 where the computation process is initializes by setting $p = 0$.

It has been observed that for increasing values of V and p the probability of clipping decreases and that it is possible to obtain arbitrarily small values of probability by increasing the number of iterations p.

The above-described embodiments are, of course, merely illustrative of the principles of the invention. Indeed, numerous other methods or apparatus may be devised by those skilled in the art without departing from the spirit and scope of the invention. Moreover, the invention may be implemented as hardware, as an integrated circuit, via programming on a microprocessor, on a digital signal processor or the like.